Recovery from acidification in boreal lakes inferred from macroinvertebrates and subfossil chironomids

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Abstract
Acidification of waters and soils caused by emissions and the long-range transport of air pollutants has been a serious worldwide problem during the last decades. The extent of the acidification problem in Finnish acid-sensitive forest lakes was examined in the Acidification Research Project (HAPRO) in the mid-1980s. The recent decline in the emissions of air pollutants has resulted in the chemical recovery of watersheds in many regions, and the present work on the recovery processes in acidified Finnish headwater lakes (REPRO) was launched to examine whether the chemical recovery has already been accompanied by biological recovery. The patterns of recovery were studied by re-sampling littoral macrozoobenthos in a subset of the previously sampled HAPRO lakes. Paleolimnological samples were taken in order to assess the possible dependence of lacustrine chironomid communities on the changing degree of acidification. Acid sensitive and moderately acid sensitive benthic species revealed slight recovery in the formerly most acidic (pH ≤ 5.5) but recently recovered lakes. The most significant factors affecting the response of benthic communities were increased mean lake pH and decreased labile aluminium concentration. Paleolimnological chironomid analysis revealed a slight response along the pH gradient, but also significant structural similarity between the present and pristine chironomid assemblages. This implies that no major changes in chironomid communities of these acidic lakes have occurred during the past centuries. The alternative future trends and threats to biological recovery in small headwater lakes are discussed.

Introduction
During the 1970s and 1980s the acidification of lakes, rivers and soils caused by emissions and long-range transport of air pollutants became a significant international concern (Kauppi et al., 1990; Keller et al., 1999; Mannio, 2001; Smol, 2002). The first and worst signs of acidification were detected in Scandinavia and North America, and at least 100 000 lakes have been impacted in these areas (Schindler et al., 1989; Minns et al., 1990; Mannio, 2001). Lakes in many parts of Scandinavia and North America are very susceptible to acidification due to their poor buffering capacity. Finnish soils derive mainly from Precambrian siliceous rocks, and the natural buffering capacity is therefore low in many parts of the country (e.g., Nuotio et al., 1990). Boreal lake ecosystems are also sensitive to acid load because of the harsh climate and the scarcity of lacustrine species (Kauppi et al., 1990: XIII).

The Finnish Acidification Research Project, HAPRO, carried out from 1985 to 1990 (Kauppi et al., 1990), was launched in order to study the extent of the acidification problem in Finland. This outstanding program included, among many other research objects, studies of macrozoobenthic responses to acidification in Finnish forest lakes (Meriläinen & Hynynen, 1990). As a result of increased deposition, an acid induced decrease in the
number of benthic species was detected, especially in the littoral zone of lakes, whereas no significant changes appeared in the biomass or number of animals. Acid sensitive species were found, especially among the snails, mayflies and small mussels, by means of which it is possible to evaluate the stage of acidification of a lake. The chemical and biological databases collected during the HAPRO project formed a major basis for the present study, carried out on a subset of the 140 lakes investigated in HAPRO.

Concerns about environmental damage have led to political actions and consequent widespread declines in the emissions of airborne pollutants in large regions of Europe and Northern America (e.g., NIVA, 1997). In the 1980s and 1990s, effective sulphur emission control programs were launched in the United States and Canada (NA-PAP, 1991; Environment Canada and U.S. Environmental Protection Agency, 1995). In Europe, the emissions of sulphur and nitrogen compounds declined by 34% (SO$_2$), 14% (NO$_2$) and 18% (NH$_3$), respectively, between 1988–1995 (Olendrznynski, 1997). Comprehensive cooperative investigations, such as the Northern Lakes Recovery Study (NLRS, Canadian/Norwegian), have been designed as multidisciplinary monitoring, experimental and modeling projects to examine the biological recovery of acid damaged waters following substantial reductions in acid deposition (Gunn & Sandøy, 2001, 2003). As a consequence of falling rates of acid deposition, increasing concern will be focused on the biota of impacted areas to address the question of whether water quality will improve and the biota will recover (Gunn & Sandøy, 2003).

The substantial reductions in air pollutant emissions, resulting from key international activities such as the protocols of the United Nations Economic Commission for Europe’s Convention on Long-Range Transboundary Air Pollution (UN/ECE CLRTAP), and legislation of the European Union, have resulted in the first clear signs of ecosystem recovery. An international study using data on long-term changes in surface water chemistry in Europe and North America showed that in concordance with declining trends in acidic deposition, lake and stream sulphate concentrations decreased in all studied regions with the exception of Great Britain (Stoddard et al., 1999). Recovery in alkalinity was observed in all regions of Europe but in only one region in North America. The lack of recovery was attributed to strong regional declines in base cation concentrations that exceeded those of sulphate concentrations. The studies carried out in Finland, based on more detailed national data than used in the study of Stoddard et al. (1999), have confirmed this general pattern (Mannio et al., 2000; Mannio, 2001).

Despite the increasing number of investigations focusing on the biological recovery of acid damaged watersheds, indications of recovering communities are still few. Probably the most promising signs of biological recovery thus far are those from Killarney Park, Canada (e.g., Smol et al., 1998; Keller et al., 2003; Findlay, 2003) and Nausta watershed, Western Norway (Halvorsen et al., 2003). In Finland, the first observations of biological recovery were made on fish populations of chemically recovering lakes in the early – 1990s (Rask et al., 1995). Profundal invertebrates have traditionally been considered as reliable indicators of the biological status of deep lakes (Sæther, 1979; Wiederholm, 1980). However, the littoral benthos has been frequently underestimated in water quality monitoring as an indicator of environmental change because of the higher spatial and temporal variation in littoral communities compared to profundal ones (Irvine et al., 2001). However, objectives included in the EU Water Framework Directive contain a view to also reaching a good ecological status in acidified surface waters, and in reaching this target the littoral benthos has great value in interpreting the biological responses to declines in the emissions of air pollutants.

The aim of this study was to examine possible changes in macrozoobenthic communities by re-sampling a subset of the previously sampled HAPRO lakes showing recent improvements in lake chemistry. We also discuss the relationships between changes in deposition chemistry vs. lake chemistry and biological change, and identify how biological recovery is connected with chemical recovery. In addition, we attempt to identify the recovery process by assessing the population responses of acid sensitive benthic invertebrates (e.g., Gastropoda, Ephemeroptera, Lamellibranchiata) to the decreasing acidity. Paleolimnological samples were taken in order to assess whether the